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Quantum oscillations and negative differential resistance in nonresonant magnetotunneling

P. A. Schulz* and C. Tejedor

Departamento de Fisica de la Materia Condensada, Universidad Autonoma, Cantoblanco, 28049 Madrid, Spain

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We predict the existence of negative differential resistance in nonresonant tunneling through a single barrier when a magnetic field is applied perpendicular to the current. Moreover, the use of a transfer Hamiltonian method for the calculation of the tunneling current allows the clear understanding of the physical origin of the experimentally observed oscillations as a function of the magnetic field. These two phenomena are consequences of the existence of individualized tunneling channels connected with anticrossings in the dispersion relation.

The application of a high magnetic field **B** perpendicular to an electronic current tunneling through a barrier produces the appearance of a series of tunneling channels connected with anticrossings in the dispersion relation.[1] The aim of this Rapid Communication is to discuss two very important consequences of the physical structure of these tunneling channels. The first one is that the current presents oscillations as a function of B for a given applied bias as has been experimentally observed in different situations.[2,3] We will discuss how this phenomenon is competing with (or better, superimposed to) the oscillations of the bulk Fermi level when the magnetic field is varied. The second consequence is even more attractive. In some conditions, the transverse magnetotunneling through a single barrier can produce negative differential resistance (NDR) in a nonresonant process. This is an interesting effect of the magnetic field that, to our knowledge, has not yet been experimentally observed.

As has been previously discussed,[1] the states at the anticrossings of the dispersion relation, shown in Fig. 1, are the only ones with wave functions in the two sides of the barrier, so that only electrons in one of those states are able to jump from one side of the barrier to the other. The best way for describing such a process is the use of a transfer Hamiltonian method (THM)[1,4] to compute the transmission probability through the barrier. In THM, the total Hamiltonian is separated in two spatial regions L (left) and R (right) in a way that

$$H \equiv H_L + V_L = H_R + V_R \,, \tag{1}$$

where $H \equiv H_L(H_R)$ in the left (right) side. $|L\rangle$ and $|R\rangle$ are the eigenstates for the left and right Hamiltonians with energies E_L and E_R, respectively, and the wave functions $\Phi_L(\mathbf{r}) = \langle \mathbf{r} | L \rangle$ and $\Phi_R(\mathbf{r}) = \langle \mathbf{r} | R \rangle$ are the wave packets of the actual problem. We take the barrier in the z direction and the magnetic field **B** along the x direction. By considering the gauge $\mathbf{A} = (0, -Bz, 0)$ the left and right electronic spectra are obtained by solving the Schrödinger equation for H_L and H_R, respectively, by means of a finite elements method.[1,5] Once the electronic spectra are obtained, one calculates the transition probability between an initial state $\Phi_L(\mathbf{r})$ and a final one $\Phi_R(\mathbf{r})$ that is given by means of a kind of Fermi's "golden rule":

$$P_{LR} = \frac{2\pi}{\hbar} |\langle R | V_L | L \rangle|^2 \delta(E_L - E_R) \,. \tag{2}$$

Equation (2) can also be written as

$$P_{LR} = \frac{2\pi}{\hbar} | T_{LR} |^2 \delta(E_L - E_R) \,, \tag{3}$$

where

$$T_{LR} = \frac{-\hbar^2}{2m_0 m^x} \int (\phi_R \nabla \phi_L - \phi_L \nabla \phi_R) d\mathbf{S}_{LR} \,, \tag{4}$$

m_0 and m^x being the free electron and effective masses, respectively. The integral is evaluated over the surface between left and right regions and reduces in one dimension to calculate the current at some points in the barrier. The current is now evaluated by summing up the transition probabilities between all the occupied states to the left and the empty ones to the right.[1] As the perturbation potential V_L (or V_R) is only a function of z, k_x and k_y are good quantum numbers and the only available tunneling

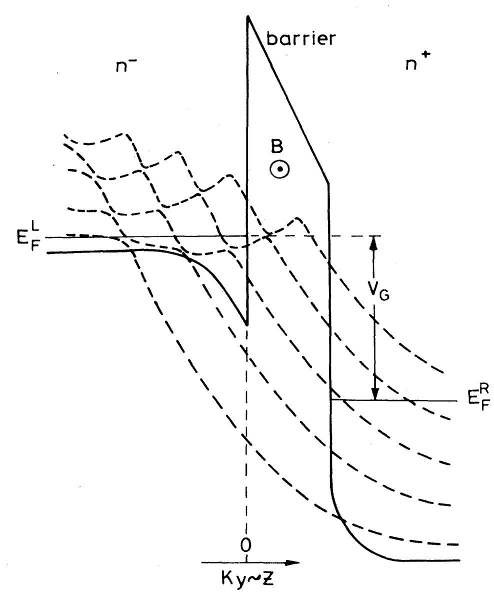

FIG. 1. Potential profile (continuous line) of a barrier with an applied bias V_G between two media with Fermi levels E_F^L and E_F^R. In the presence of a magnetic field B parallel to the interfaces, the magnetic levels (dashed lines) are functions of k_y or its associated orbit center (Refs. 1, 3, and 5).

channels are given by the crossings of the two dispersion relations E_{Ln} and $E_{Rn'}$, where n (n') is the level index corresponding to the left (right) side. These crossings correspond to anticrossings in the spectra of the total Hamiltonian H shown in Fig. 1.

In this scheme, the whole problem reduces to (i) the determination of the channels (crossings) with energies between the Fermi levels of the two sides and (ii) the calculation of the transmission at the crossings by means of Eq. (4). Our interest is to show that the step (i) is responsible for some of the oscillations of the current as a function of the magnetic field, while the step (ii) is responsible for the possible appearance of NDR.

In order to analyze these questions, we improve previously reported models[1] along two very important lines. First, we allow the possibility of an asymmetric case in which a nondegenerate semiconductor is placed to the left side of the barrier while a degenerate one is to the right. In this way the tunneling process takes places from only one magnetic level to the left to several magnetic levels at the right. In this situation, the results are easier to analyze than the case of two degenerate components so that physical consequences can be drawn. Second, we include in the potential profile the effect of band bending due to accumulation and depletion layers, respectively, appearing at the two sides so that the applied bias does not drop only at the barrier.[2,6,7]

Let us start with the first point mentioned above. This requires the calculation of the current which can be performed as carefully described in Ref. 1. We apply that formalism to the case[2] of a barrier of 230 Å of $Ga_{0.63}Al_{0.37}As$ between a nondegenerate substrate of GaAs ($N_s = 1.7\times10^{15}$ cm^{-3}) and a degenerated gate of GaAs ($N_G = 9\times10^{17}$ cm^{-3}). The dispersion relation of this system with a magnetic field parallel to the barriers and an applied bias V_G is schematically depicted in Fig. 1. Figure 2 shows the current density as a function of $1/B$ for $V_G = 0.4$ V. The periodic oscillations are due to the opening of successive new tunneling channels (crossings in the THM) between the two Fermi levels when B is varied. The periodic behavior can be understood in terms of the crossings positions with respect to the barrier. The upper part of Fig. 2 shows that each tunneling channel moves linearly with $1/B$. Moreover, when the crossing is above the left Fermi level (which is higher in energy than the right Fermi level), it does not carry current through the barrier. This cutoff of successive channels is also linear in $1/B$ as shown in Fig. 2. Therefore, the current presents oscillations in $1/B$ with a period Δ_i. There is not an appreciable effect when a crossing disappears below the Fermi level of the right because at such energy the transition probability is already very small. The interface mechanism is not the only one able to produce these kinds of periodic oscillations. On top of it, similar oscillations of period Δ_b are produced by the dependence of the bulk Fermi level with B. The latter is very weak in the case of a nondegenerate substrate but it gives strong oscillations in $1/B$ for a system with two degenerate semiconductor contacts. In Fig. 3 we show the current density as a function of $1/B$ through a barrier of 200 Å of $Ga_{0.68}Al_{0.32}As$ with an applied bias $V_G = 0.3$ V between two GaAs media with

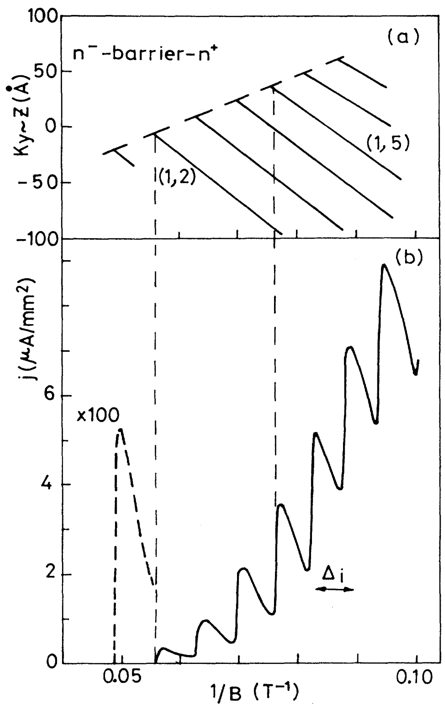

FIG. 2. (a) Position (continuous lines) (in Å) of the tunneling channels (crossings in THM) as a function of $1/B$ (in T^{-1}) for the sample of Ref. 2 described in the text with a bias $V_G = 0.4$ V. The dashed line stands for the cutoff of these channels giving the oscillations of the current (see text). Numbers in parentheses (n,n') label the crossing between the nth magnetic level of the left with the n'th of the right. (b) Current density j (in μA/mm^2) as a function of $1/B$ (in T^{-1}) for the same system. Δ_i is the period of the oscillations.

a doping of 10^{18} cm^{-3}. Clearly, two sets of oscillations are observed. The calculated dependence of j with B shown in Figs. 2 and 3 has been experimentally observed.[2,3,8] The existence of two different sets of oscillations in $1/B$ has been clearly detected in some cases[3] (although attributed to some different origin) while in other cases only indications of a second set of oscillations are given.[2,8]

A rather more important phenomenon appears when the current is studied as a function of the bias V_G for a fixed magnetic field. From a semiclassical point of view, the magnetic field bends the electron trajectories so that, for any value of B, a threshold bias is required for having tunneling current. The quantum description of this threshold is that it is the potential required to open the first tunneling channel which manifests itself in a steplike increase of the current. The continuous increase of the bias lowers the energy of the channel more rapidly than the lowering of the barrier. Therefore, it reflects in a higher effective barrier seen by the electrons. This produces a lowering of the transmission probability T_{LR} and consequently of the current density as is shown in Fig. 4 for the same system[2] of Fig. 2 for different values of B. This is the origin of the NDR which is here not connected with resonant effects which are the common mechanism

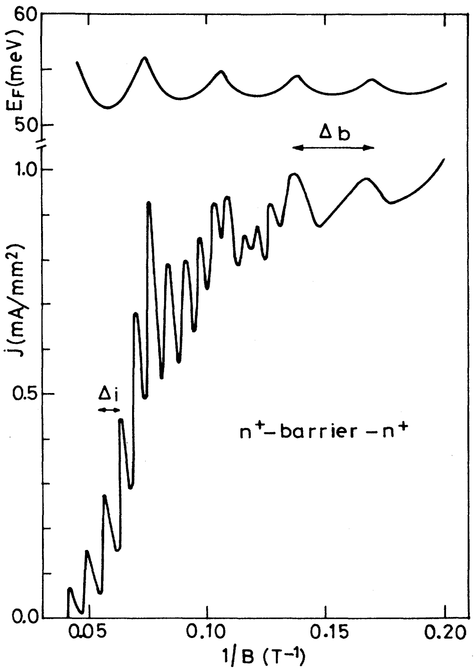

FIG. 3. Current density (in mA/mm^2) and Fermi level (in meV) as a function of $1/B$ (in T^{-1}) between two GaAs crystals with a doping of 10^{18} cm^{-3} separated by a barrier of $Ga_{0.68}Al_{0.32}$ with a bias of 0.3 V. Δ_i and Δ_b are the oscillations periods (see text).

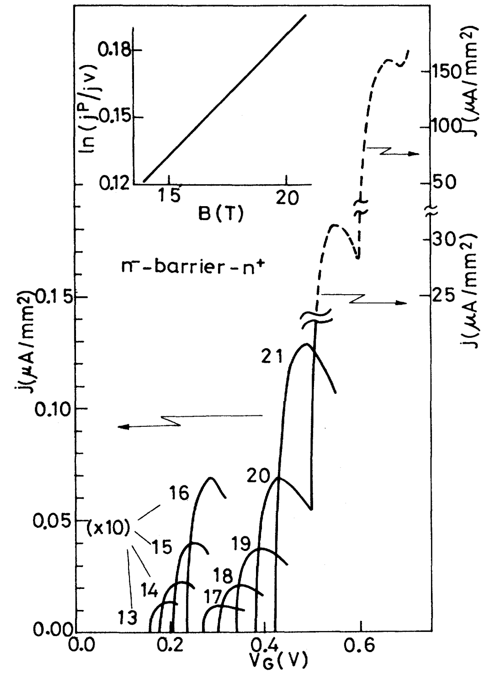

FIG. 4. Current density (in μA/mm^2) as a function of the bias V_G for the system (Ref. 2) of Fig. 2 for different magnetic fields (in T). The inset shows the logarithm of the peak/valley ratio (NDR) for the first peak of j as a function of the magnetic field.

producing this phenomenon. When the bias is high enough, a second tunneling channel is open and the process starts again as is shown in Fig. 4 for 20 T. These features produced by the magnetic field are superimposed to the usual exponential increase of the current with bias.[4] Therefore, any peak in the current moves to higher bias with increasing B and becomes higher exponentially. Since the valley current has the same behavior but with a lower exponential factor, the peak-to-valley ratio (j^p/j^v) of the NDR also increases exponentially with B as is shown in the inset of Fig. 4. The peak-to-valley ratio is smaller for higher channels but the behavior of any of them is qualitatively the same. To our knowledge, no experimental evidence of NDR has been reported in these systems probably because rather high magnetic fields are required.

In summary, in this Rapid Communication we have studied two different types of quantum oscillations in the tunneling current through a barrier having a magnetic field applied perpendicular to j. These oscillations are easier to study when the substrate is a nondegenerate semiconductor while the gate is a degenerate one because only one magnetic level at the left side is involved. It is shown that bending effects are important only quantitatively but not qualitatively. When the bias is fixed, j presents periodic oscillations as a function of $1/B$ coming from two different sources: (i) the usual periodicity due to the variation of the bulk Fermi level and (ii) the dependence on B of the opening of tunneling channels. These channels are connected with the anticrossings of the magnetic levels with energies between the two Fermi levels of the substrate and the gate. More appealing is the existence of NDR when B is fixed. This feature is not connected here with resonance effects but with the dependence of the transmission probability with the applied bias. Such transmission decreases when V_G increases (lowering the current until a new tunneling channel is open) because the lowering in energy of the tunneling channels dominates on the lowering of the barrier giving a higher effective barrier for the tunneling.

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*On leave from Instituto de Fisica of Universidade Estadual de Campinas, Caixa Postal 6165, 13081 Campinas, São Paulo, Brazil.

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